New Limits on Sterile Neutrino Mixing with Atmospheric Neutrinos

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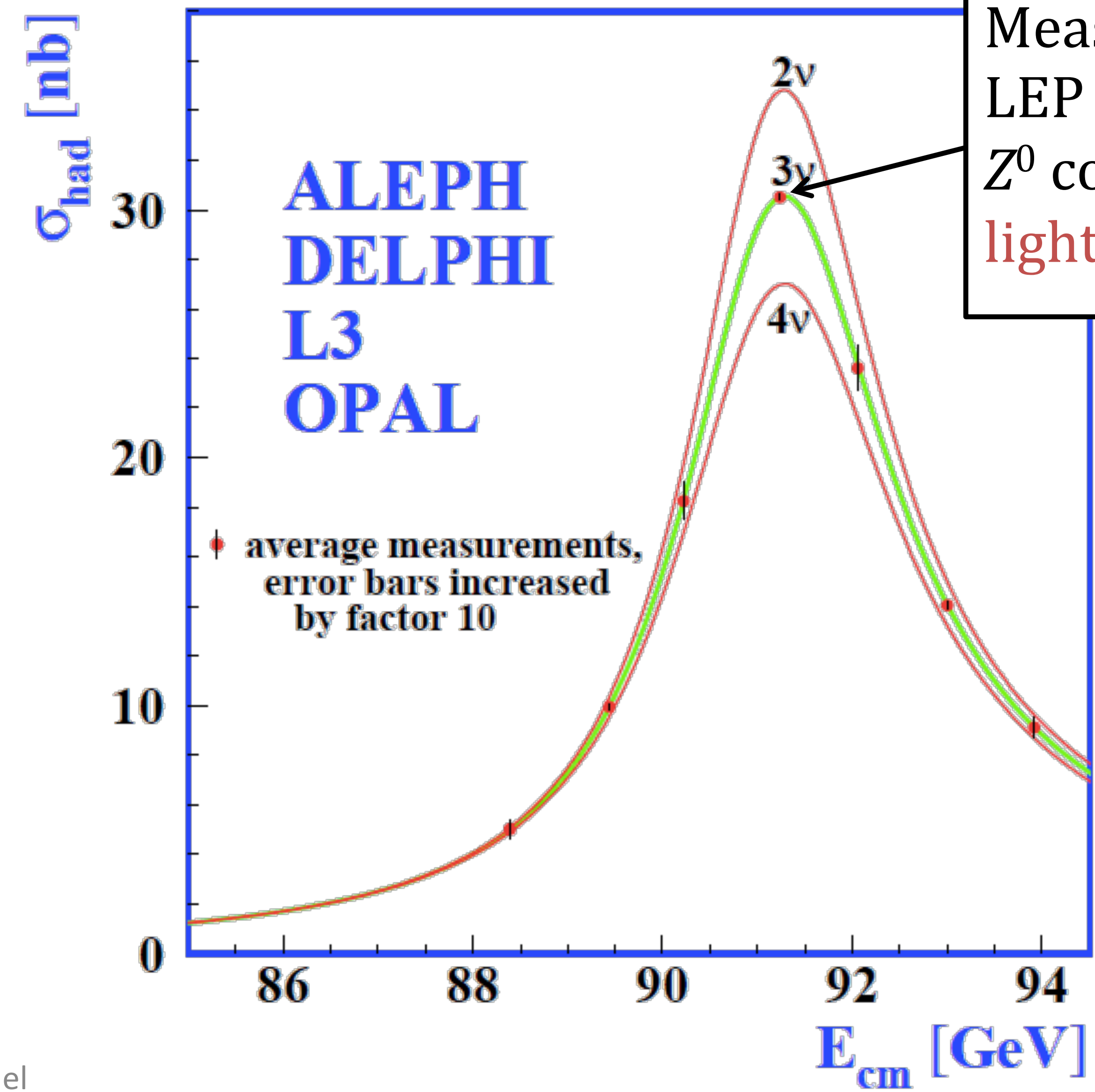
for the

The Super Kamiokande Collaboration

13th International Conference on Topics in Astroparticle and Underground Physics

September 12th, 2013

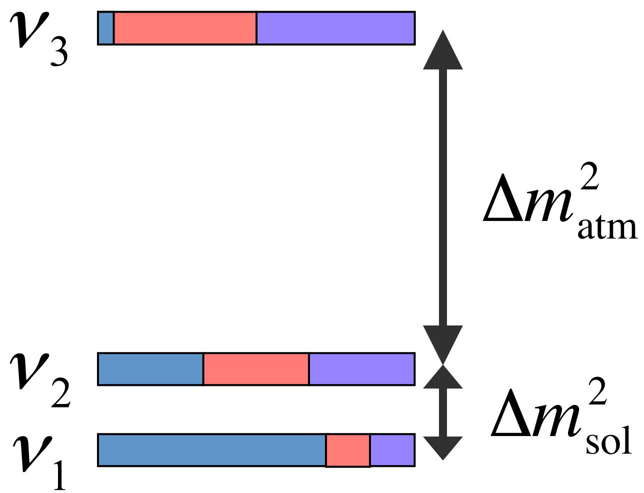
What is a Sterile Neutrino?



Measurements at LEP tell us that the Z^0 couples to only 3 light neutrinos

What is a Sterile Neutrino?

3 neutrinos ➡ 2 mass splittings



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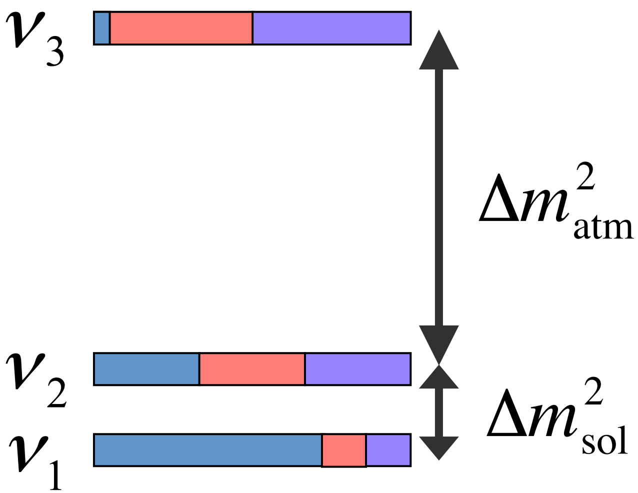
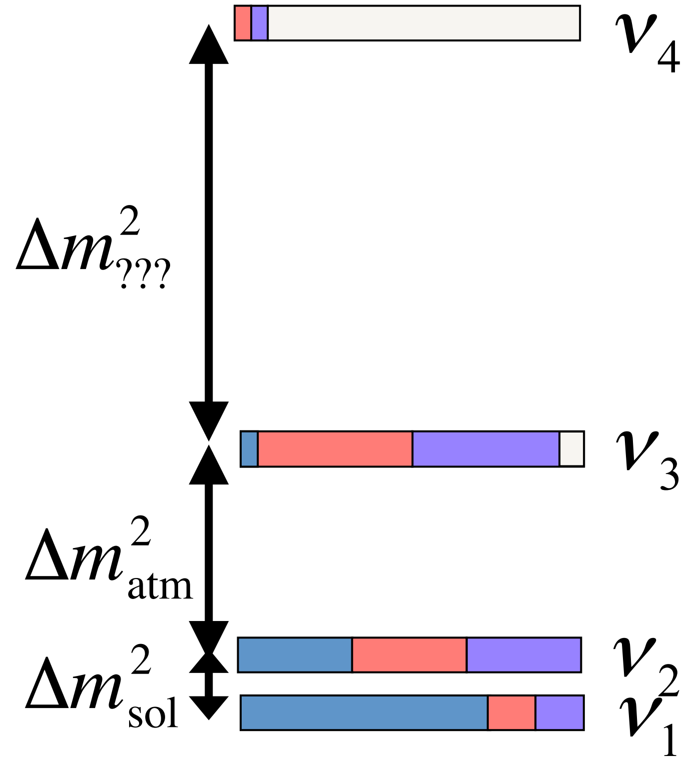
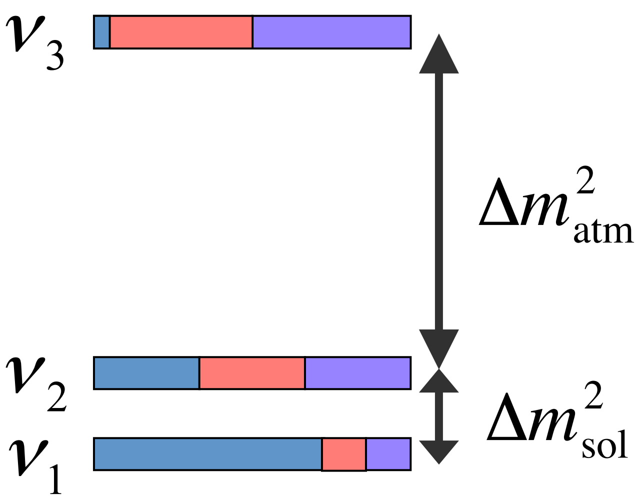


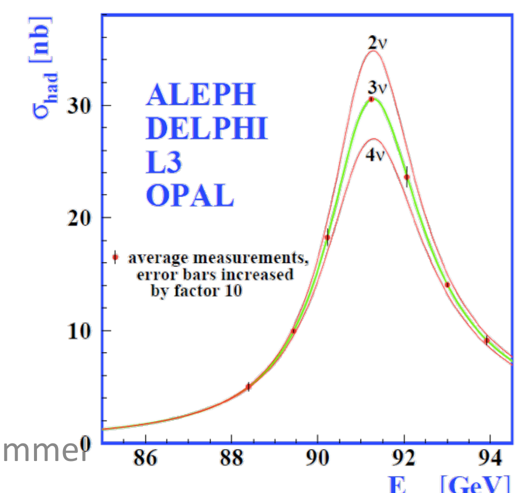


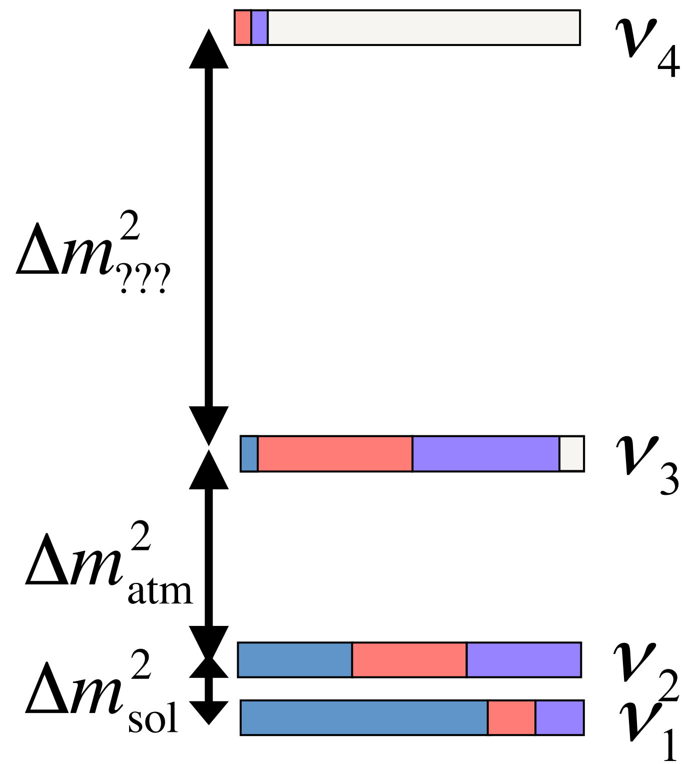
3 mass splittings ➡ 4 neutrinos

What is a Sterile Neutrino?

3 neutrinos ➡ 2 mass splittings







3 mass splittings ➡ 4 neutrinos

One of which does not couple to the Z and so does not interact weakly, i.e. **sterile**

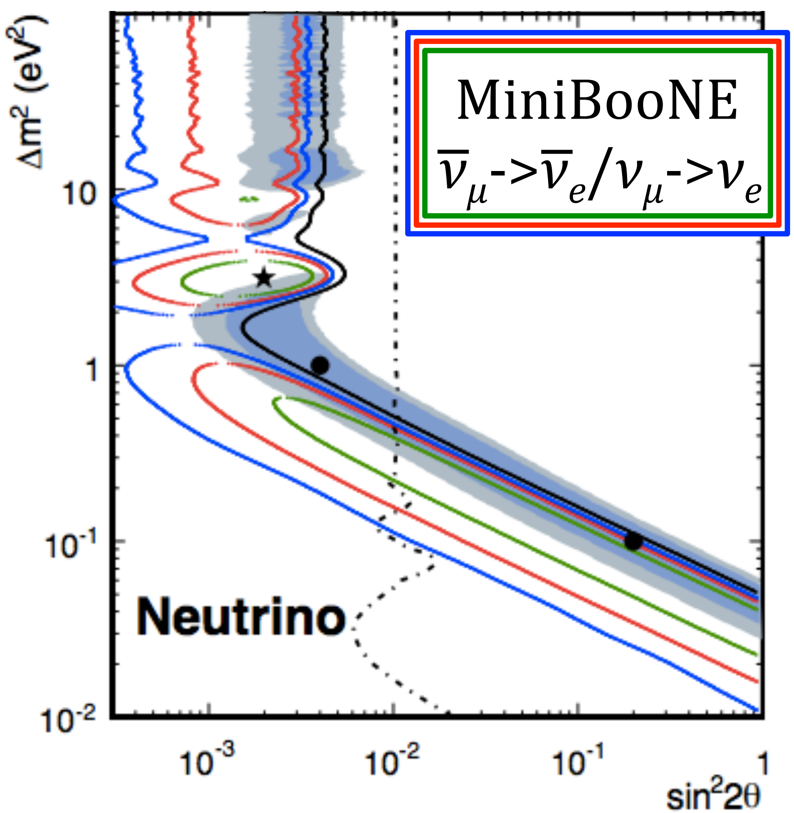
What is a Sterile Neutrino?

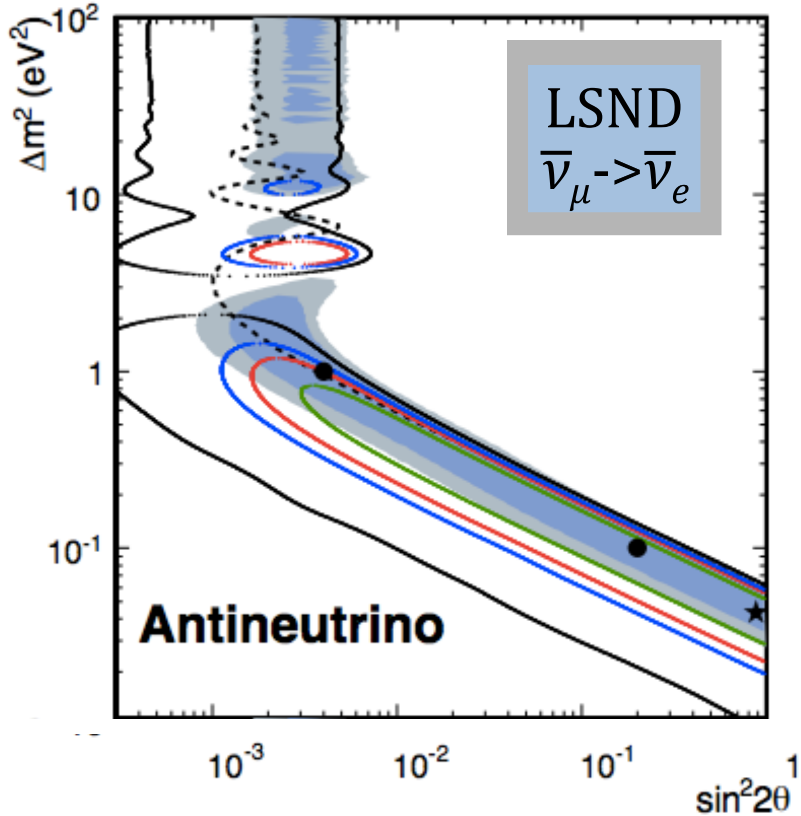
$$U = \begin{array}{c} \text{PMNS} \\ \left(\begin{array}{cccc} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{array} \right) \end{array}$$

- One more neutrino adds 7 complex matrix elements
  - but not all independent.
- 1 Δm^2, 3 "angles", 2 phases – varying parameterizations
  - $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2$ or $\theta_{14}, \theta_{24}, \theta_{34}$
- One more neutrino adds 8 more parameters

Evidence of Sterile Neutrinos

$\Delta m^2 \approx 0.1 - 10\,\mathrm{eV}^2$





PRL110, 161801 (2013)

2-flavor approx.

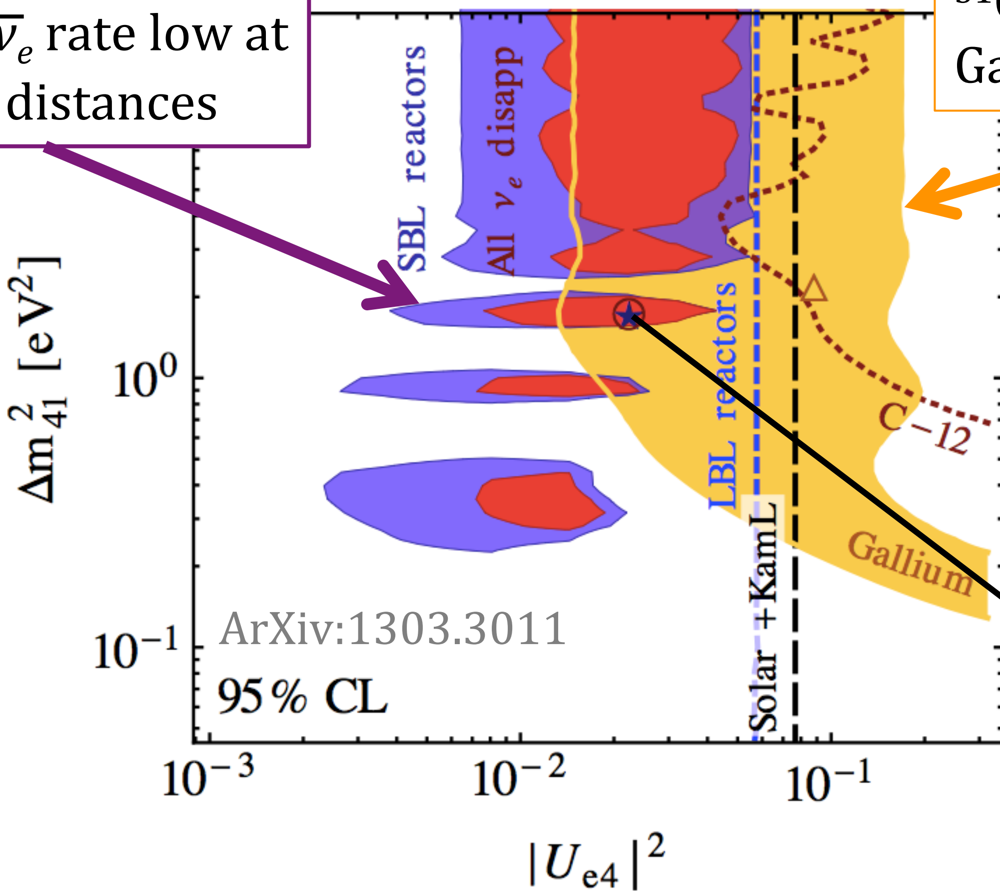
$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

Both $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ must be > 0 for non-zero probability

Evidence of Sterile Neutrinos

Reactor $\overline{\nu}_e$ rate low at short distances

$^{51}Cr/^{37}Ar$ ν_e rates low at Gallium experiments



$$|U_{e4}|^2 \approx 0.02$$
$$\Delta m^2 > 1\ \mathrm{eV}^2$$

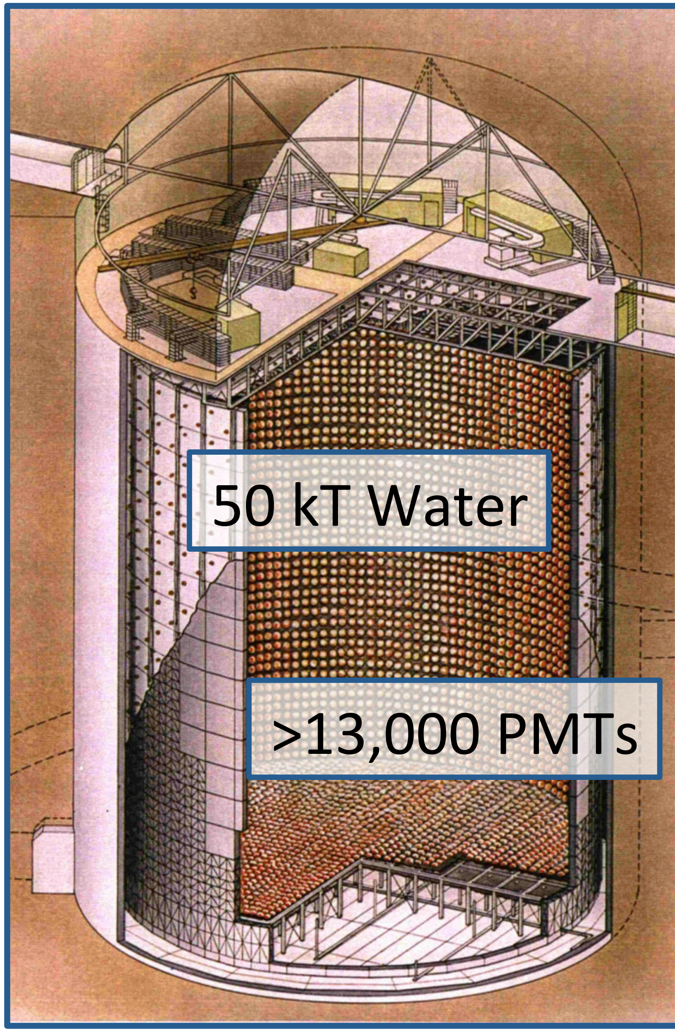
2-flavor approx.

$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

What can Super-K tell us?

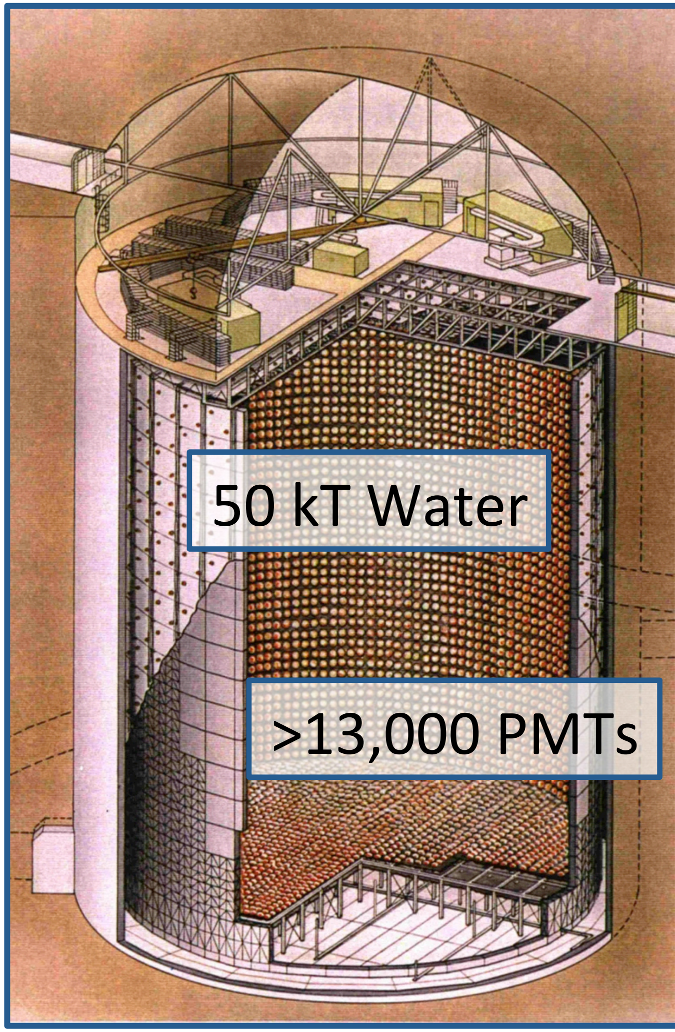
- 11 years of atmospheric neutrino data.
  - Covering a wide range of L and E
- It is most useful because of what it is *not* sensitive to:

The size of the sterile mass splitting →	Oscillations appear "fast"
The number of sterile neutrinos →	3+1 and 3+N models look the same



What can Super-K tell us?

- Short-baseline-related: $|U_{\mu 4}|^2$
  - Driven by new Δm^2
  - Creates fast oscillations across a wide range of ν_μ samples
- Atmospheric/long-baseline: $|U_{\tau 4}|^2$
  - Accessible *only* at long distances
  - Oscillations into ν_s instead of ν_τ
  - Introduces a new matter effect



Super-K Sterile Model

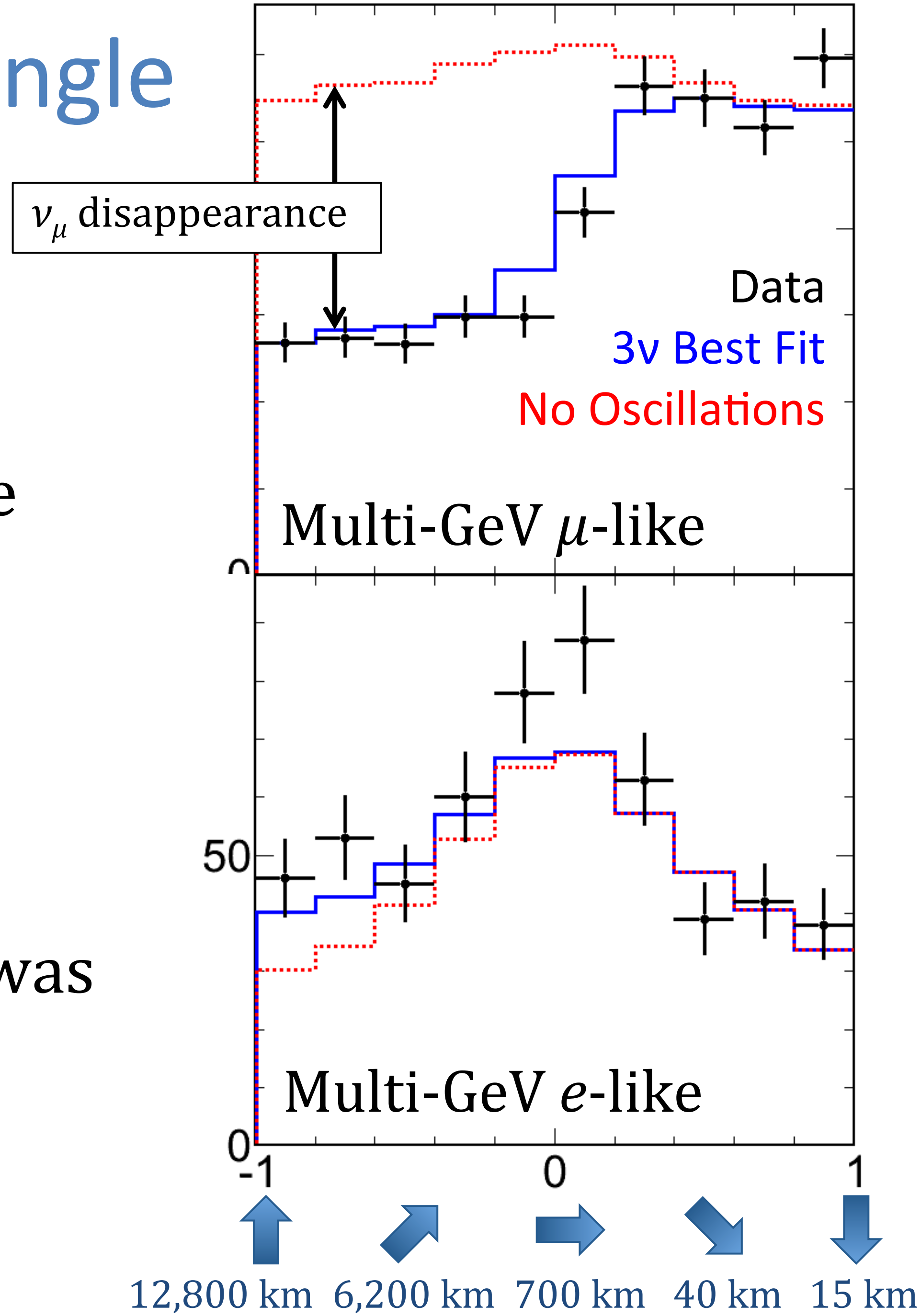
- A fully generic sterile model is difficult computationally
  - Cannot calculate both active (ν_e) and sterile (NC) matter effects together

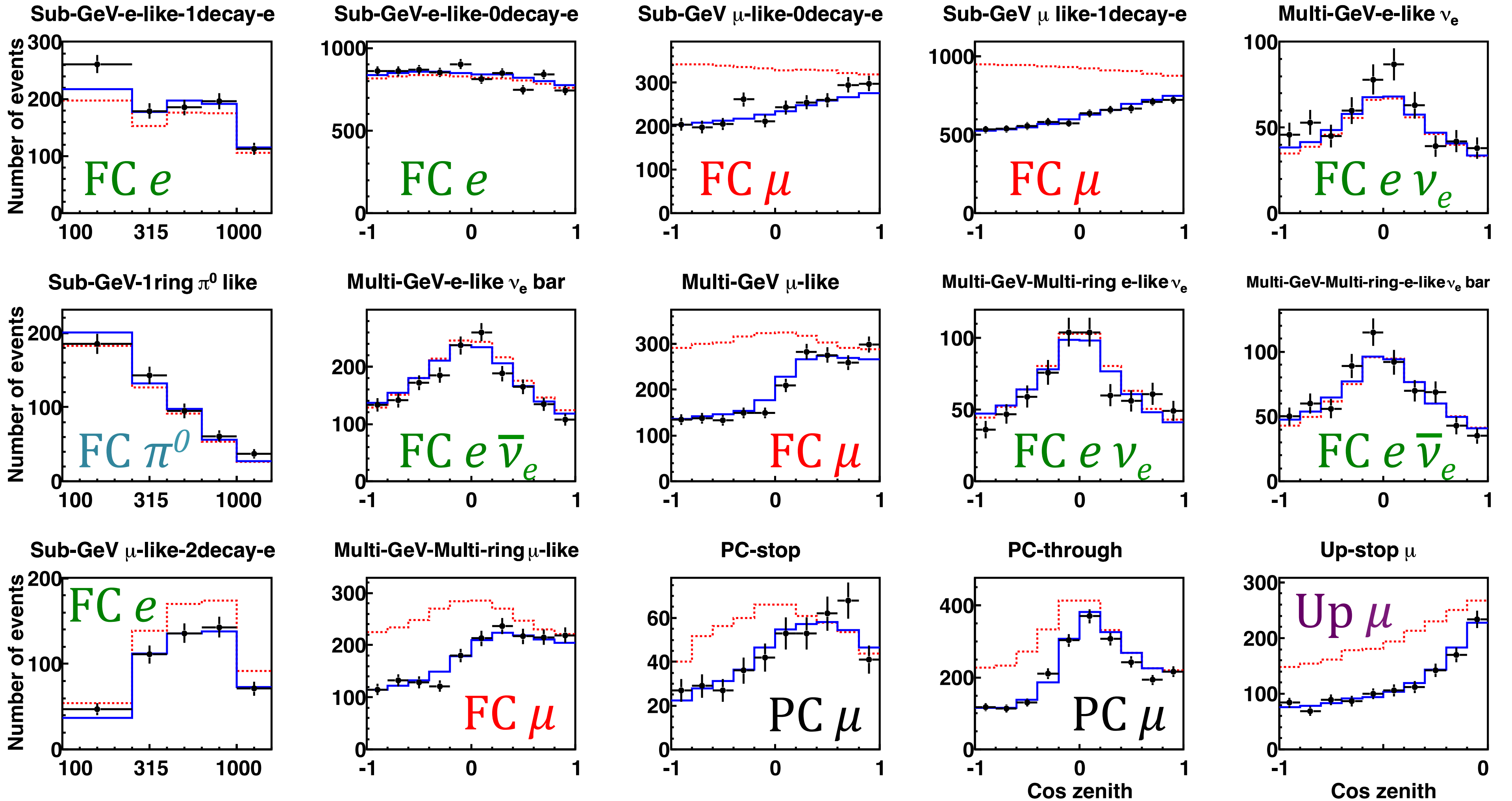
- So, we need to perform 2 different fits:

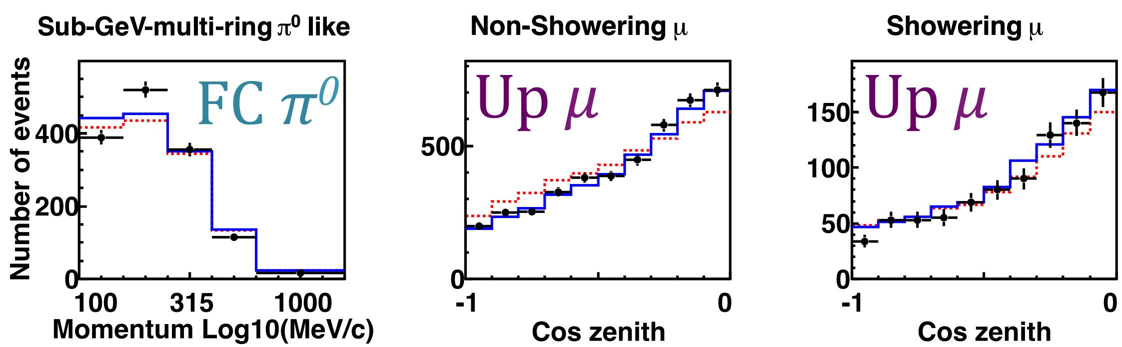
Fit for $|U_{\mu 4}|^2$	Fit for $|U_{\tau 4}|^2$
– ν_e matter effects only – Most accurate $|U_{\mu 4}|^2$ limit – No $|U_{\tau 4}|^2$ limit	– NC matter effects only – Required for $|U_{\tau 4}|^2$ – Over-constrains $|U_{\mu 4}|^2$

SK Analysis: Zenith Angle

- Look for change in flavor content vs. L
- Bin by angle and separate μ and e
  - isolate oscillations
  - other samples control systematics
- The original SK analysis was simple: up/down, μ/e







Same philosophy, more samples

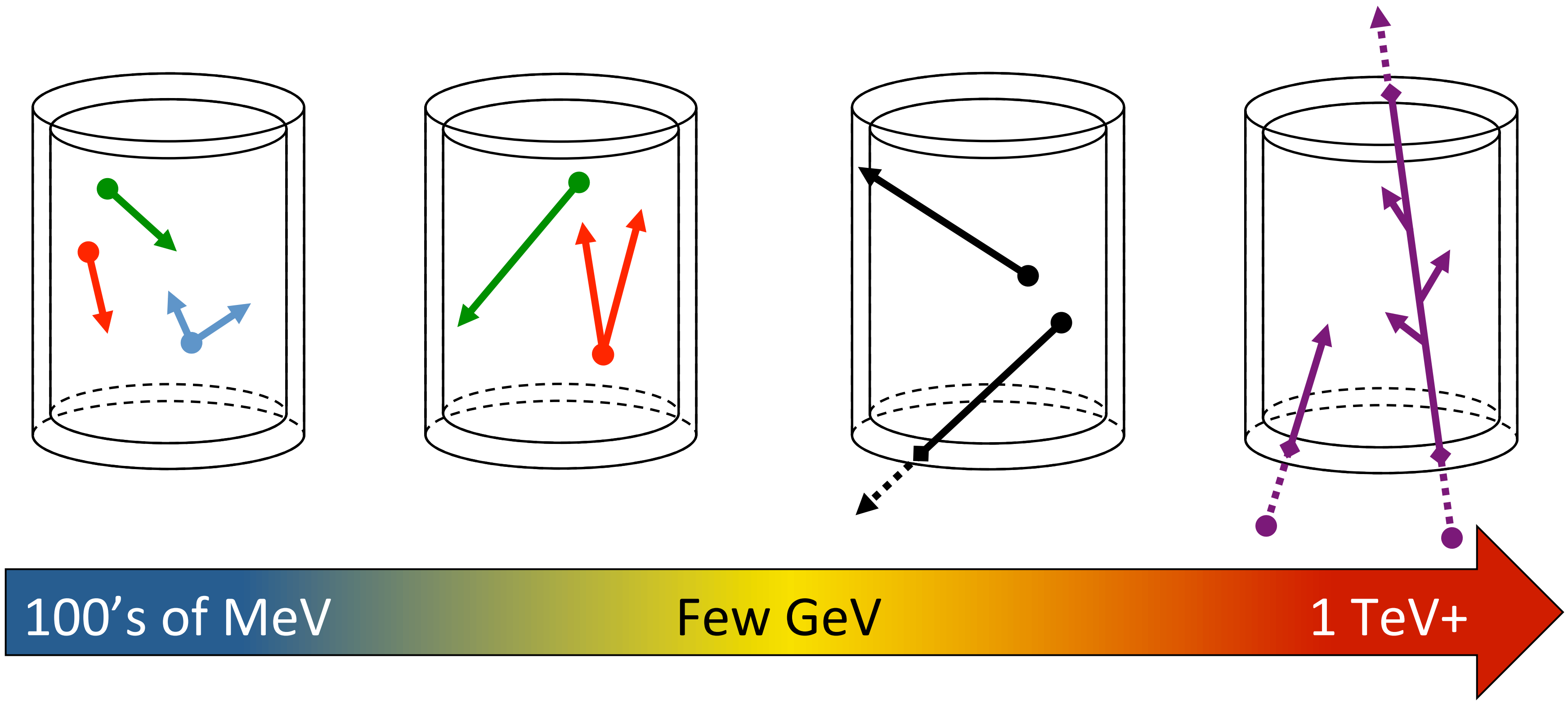
Most samples binned in angle & energy

Fully Contained

Sub-GeV Multi-GeV

Partially Contained

Up-going μ



μ-like, e-like $(\nu_e/\bar{\nu}_e)$, NCπ^0-like

Low energy ->

Poor $\cos\theta_z$ resolution

Long tracks – all μ-like

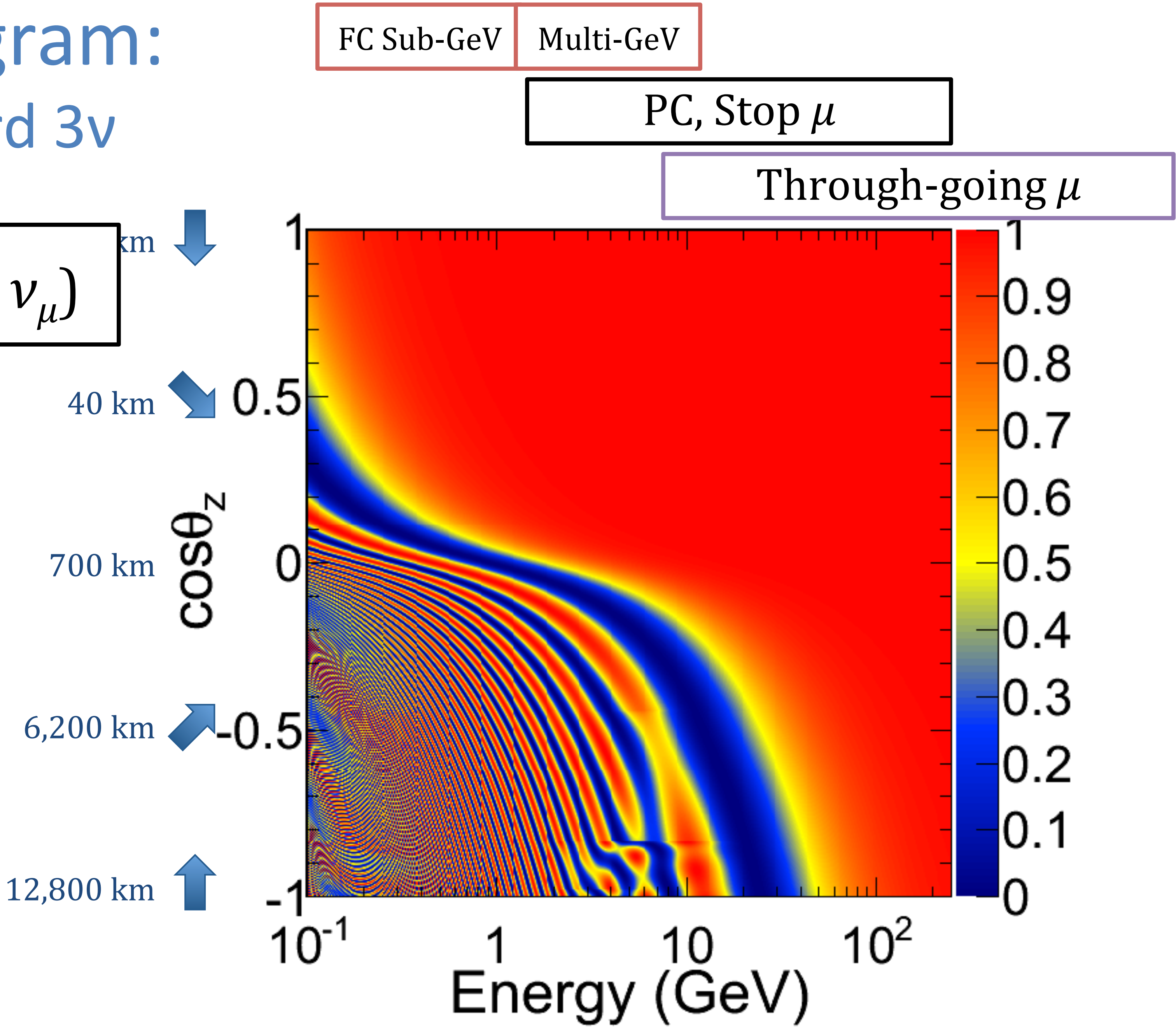
Uncontained ->

Poor E resolution

Oscillogram:

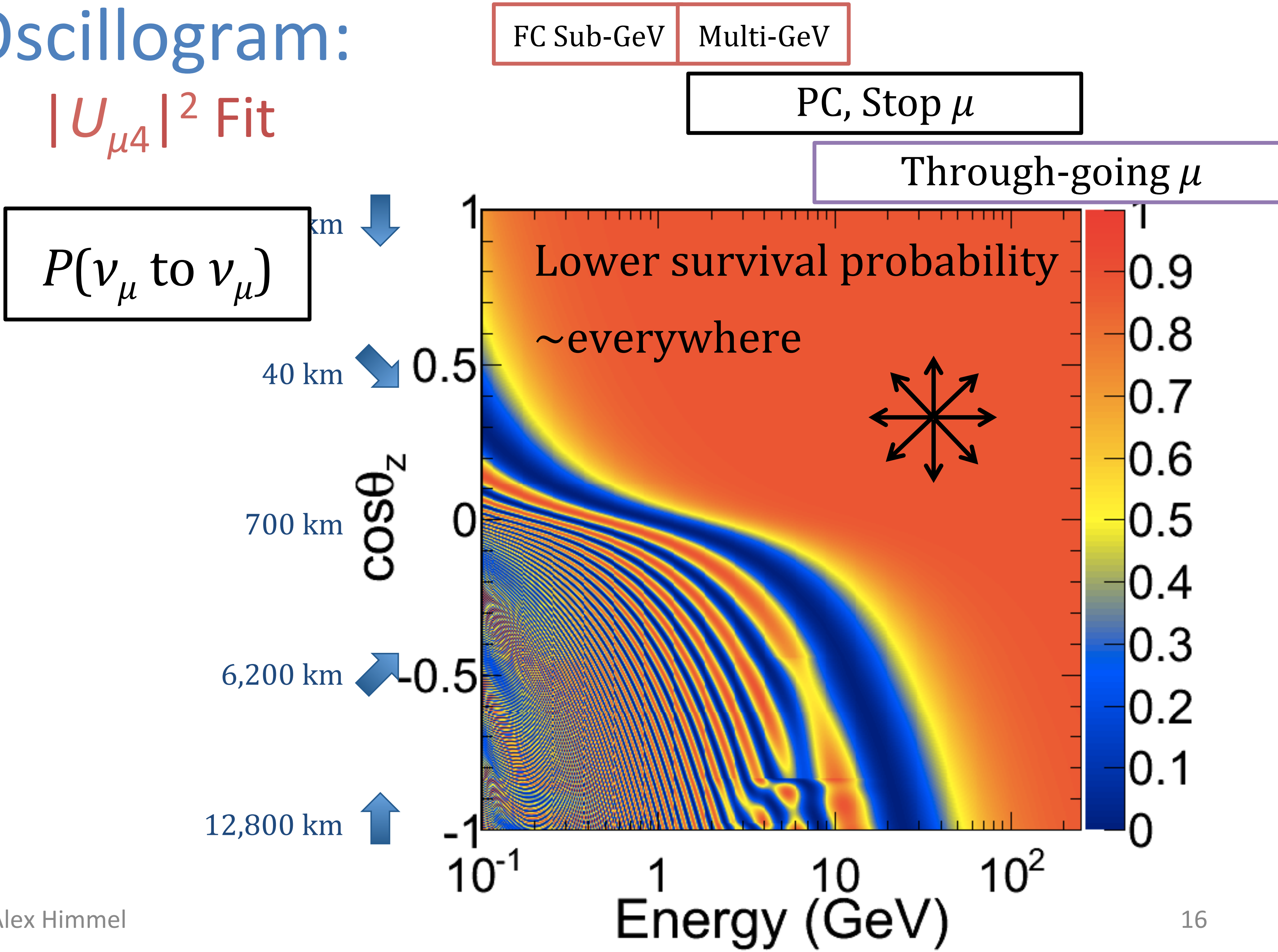
Standard 3ν

$P(\nu_\mu \text{ to } \nu_\mu)$

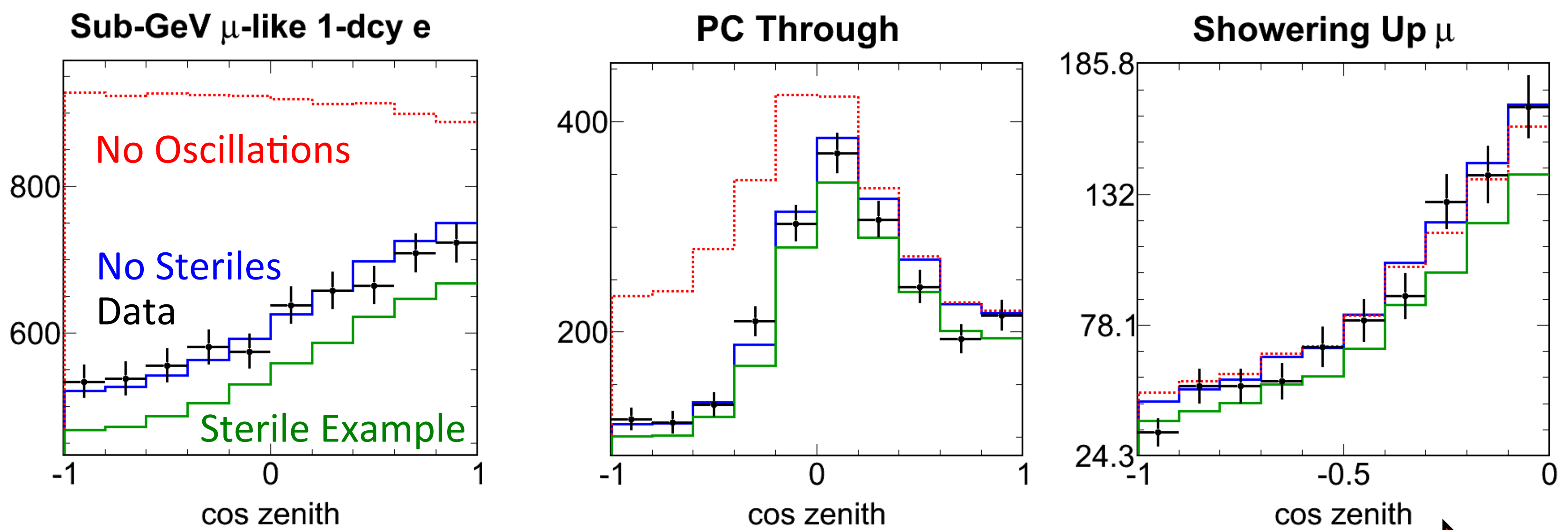


Oscillogram:

$|U_{\mu 4}|^2$ Fit



Fit for $|U_{\mu 4}|^2$



- Signature is extra disappearance in all μ samples
  - Correlated change at all energies, all $\cos\theta_z$
  - Sensitivity limited by μ/e flux uncertainty

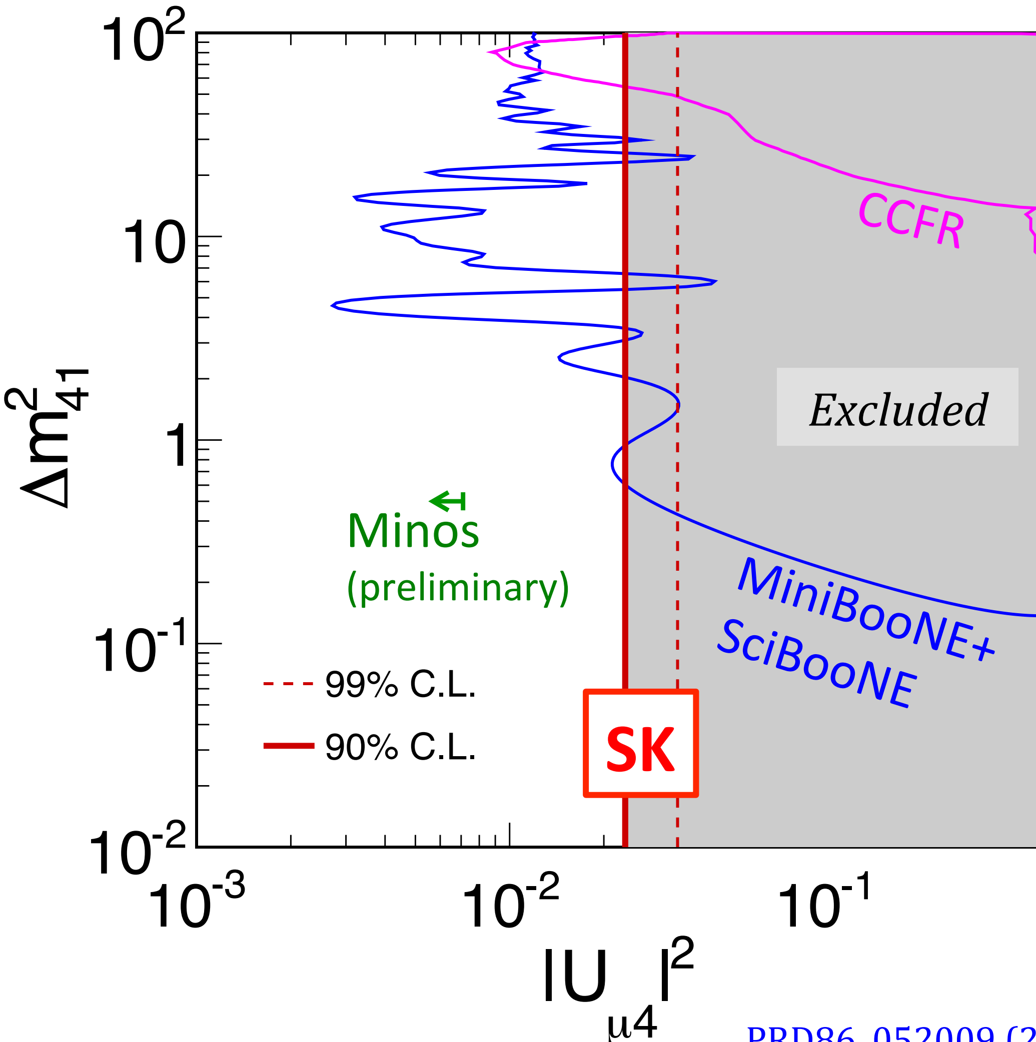
Need to do 2 fits since we cannot calculate ν_e and NC matter effects simultaneously

Fit for $|U_{\mu 4}|^2$

$|U_{\mu 4}|^2 < 0.023$ at 90% C.L.

$|U_{\mu 4}|^2 < 0.034$ at 99% C.L.

As with similar experiments, no sterile-driven ν_μ disappearance



PRD86, 052009 (2012)

PRL52, 1384 (1984)

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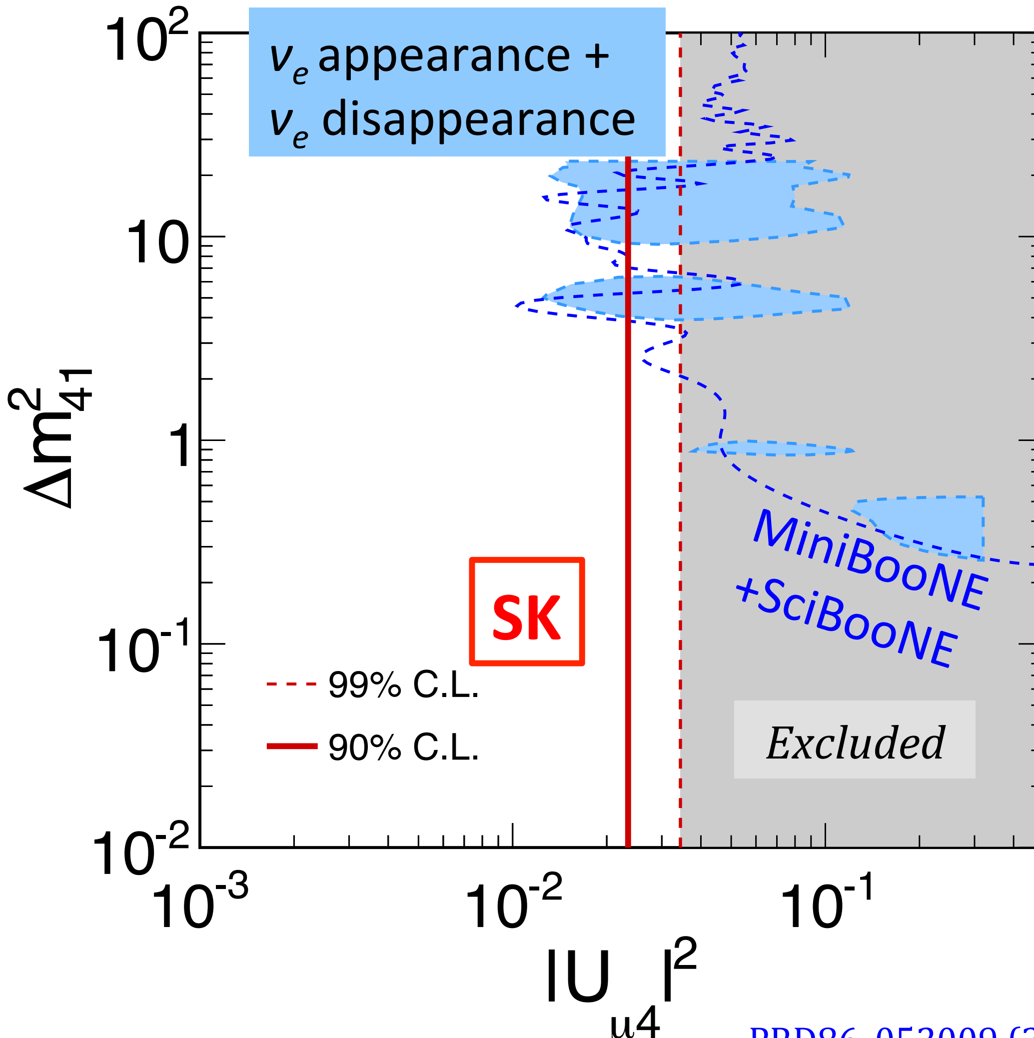
Exclude much of the MiniBooNE appearance signal



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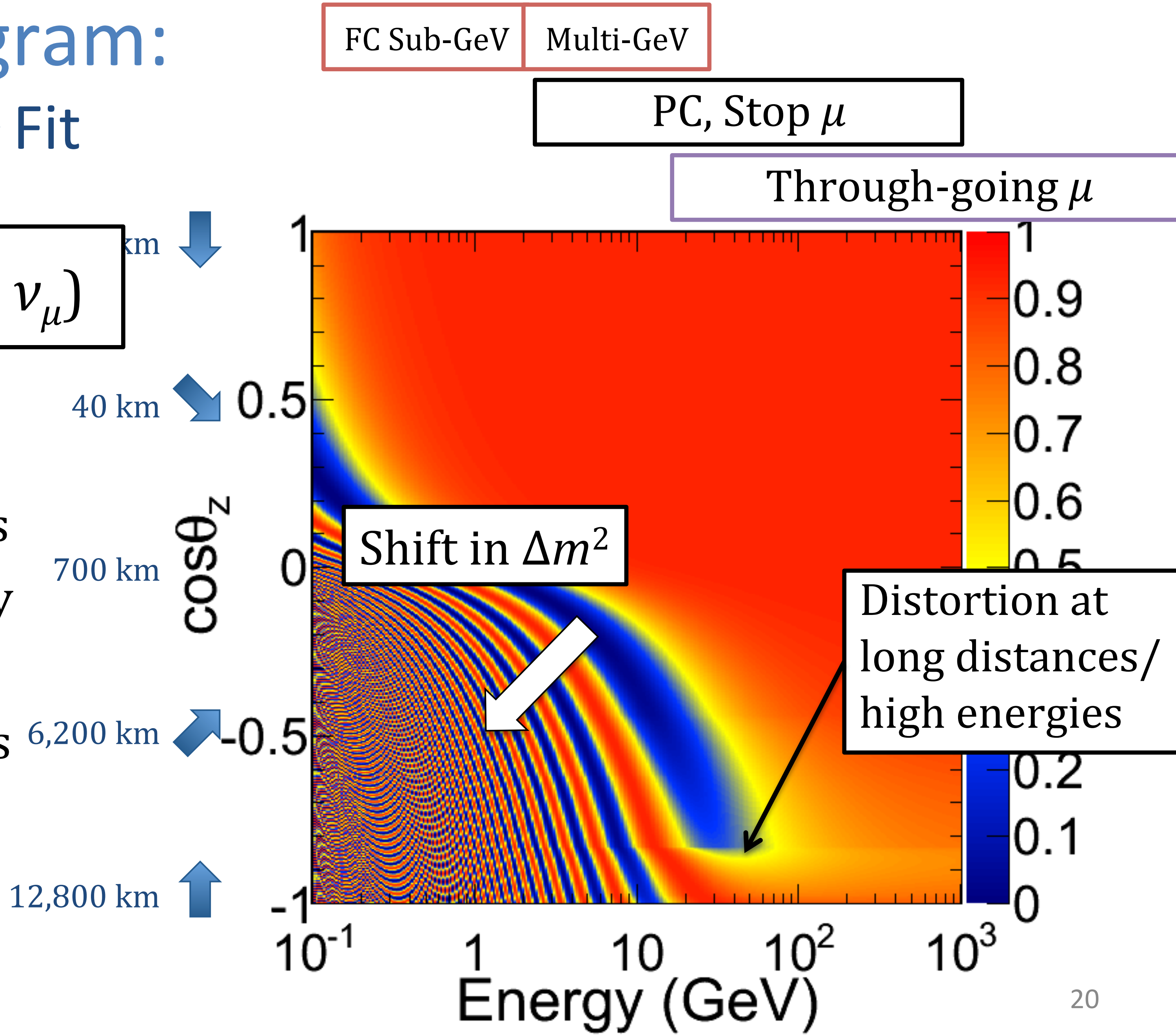
PRD86, 052009 (2012)

ArXiv:1303.3011

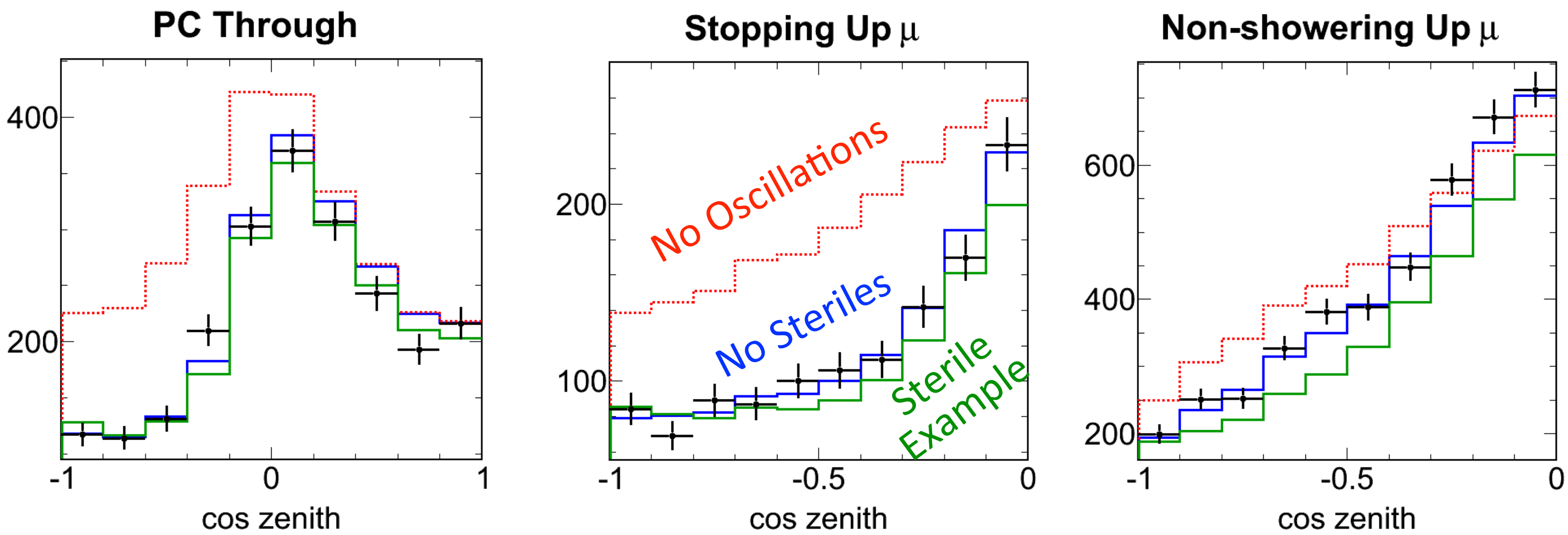
Oscillogram:
$|U_{\tau 4}|^2$ Fit

$P(\nu_\mu \text{ to } \nu_\mu)$



Potentially large changes introduced by sterile/NC matter effects

Fit for $|U_{\tau 4}|^2$ (with $|U_{\mu 4}|^2$)



5-100 GeV

- Matter effects create shape distortion in PC/Up-μ zenith distribution
  - Less disappearance in most upward bins, still have extra disappearance in downward bins

Need to do 2 fits since we cannot calculate ν_e and NC matter effects simultaneously

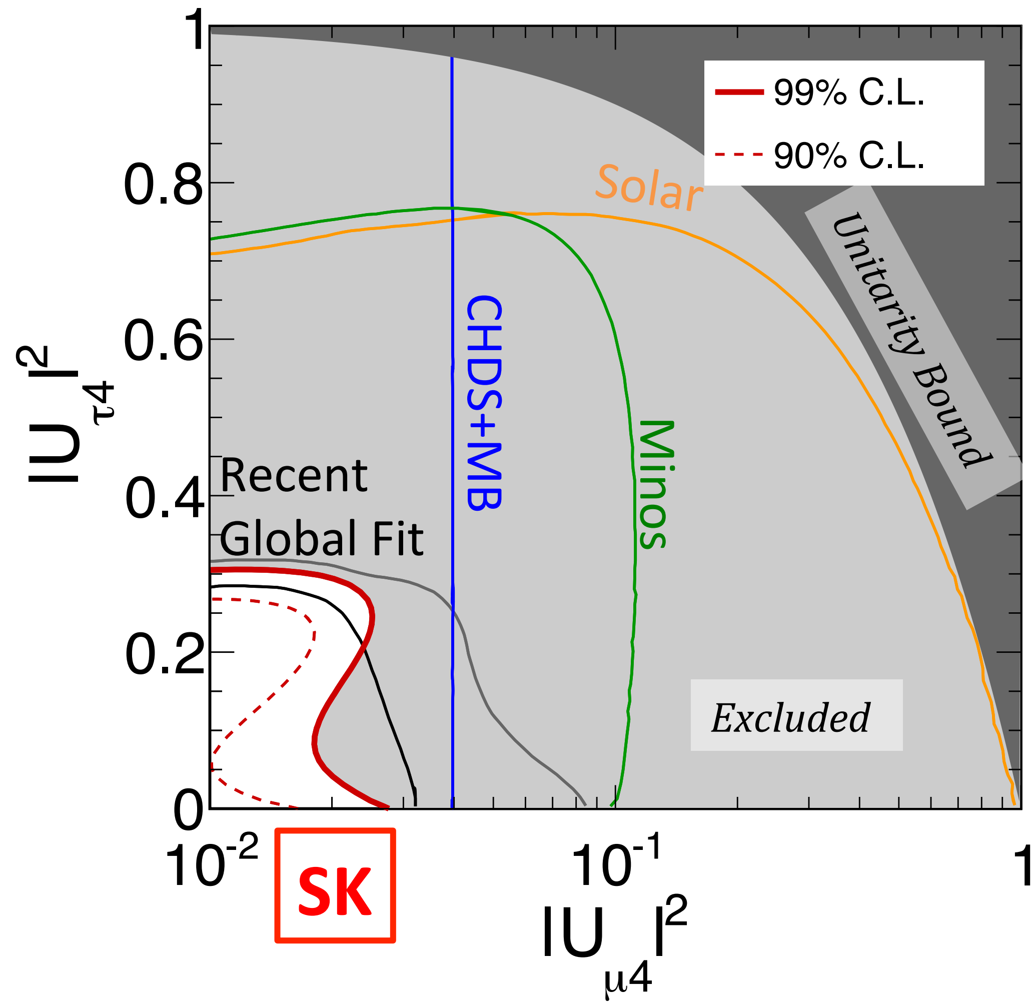
Fit for $|U_{\tau 4}|^2$ (with $|U_{\mu 4}|^2$)

$|U_{\tau 4}|^2 < 0.28$ at 99% C.L.

Favors μ to τ oscillations over μ to s

Lack of sterile matter effects places a strong constraint

- Note, $|U_{\mu 4}|^2$ is over-constrained in this fit



All comparisons from: ArXiv:1303.3011

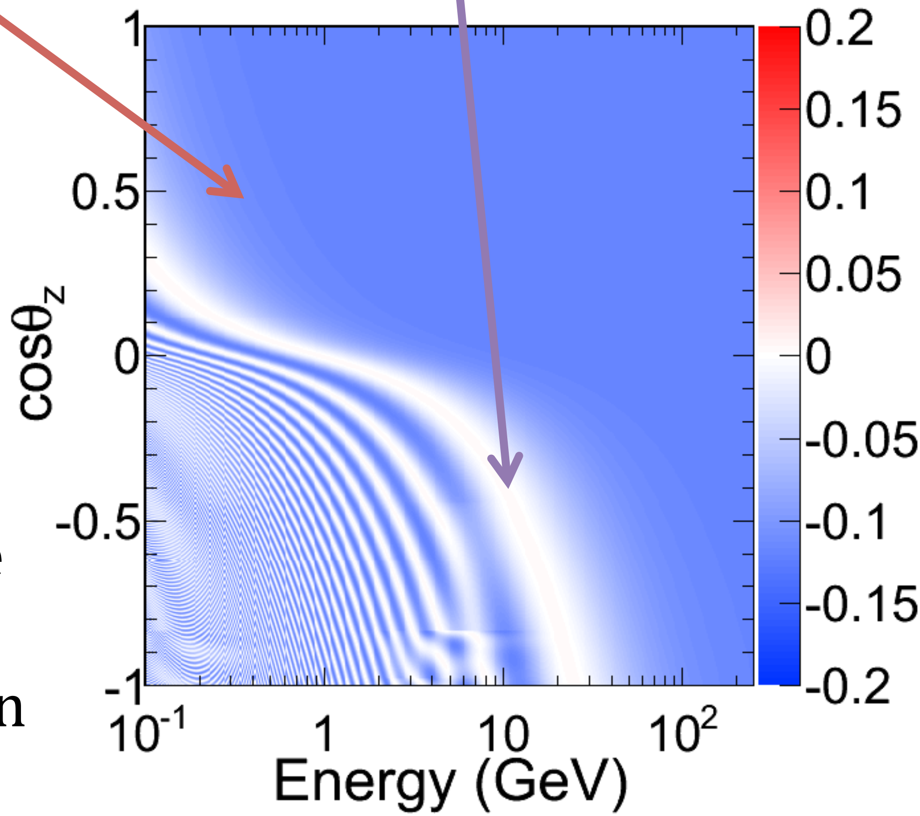
Conclusions

- Atmospheric neutrinos provide a useful tool to study sterile oscillations
  - Wide range of L/E
  - Measurement independent of Δm^2 and $N_{\text{sterile}} > 1$
- No evidence of sterile neutrinos seen
  - No sterile-driven ν_μ disappearance, consistent with other short- and long-baseline measurements
  - μ to s oscillations strongly disfavored by the lack of sterile matter effects

3+N ≈ 3+1 for Super K

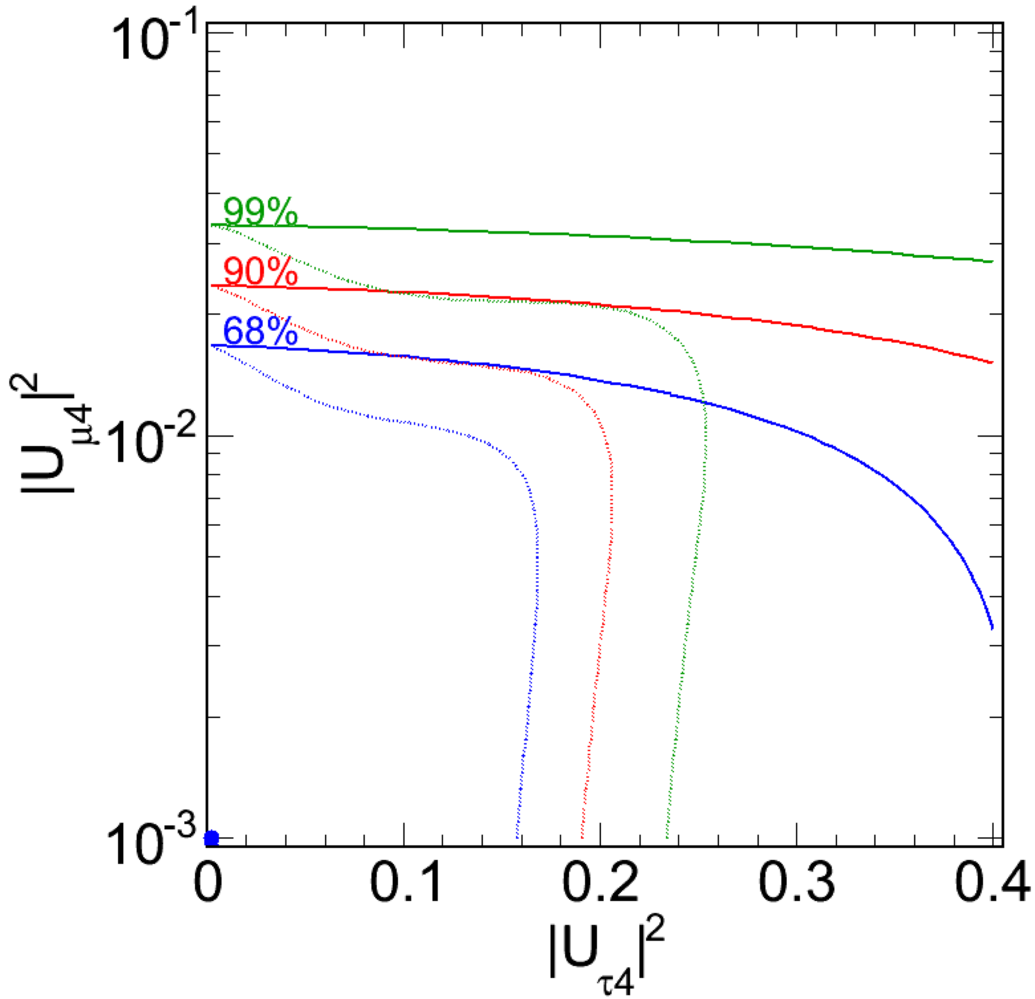
$$P_{\mu\mu} = \boxed{\left(1-|U_{\mu 4}|^2\right)^2} P^0_{\mu\mu} + \boxed{\sum_{i\geq 4} |U_{\mu i}|^4}$$

- The first sterile term:
  - Controls extra disappearance
  - Is the same for any $N_{sterile}$
- The second sterile term:
  - Fills in the minima
  - Varies for $N_{sterile}$
- Our experiment is *much* more sensitive to first term
  - Beam experiments, focusing on the first oscillation dip, *are* sensitive to the second term.



No Matter in 3ν

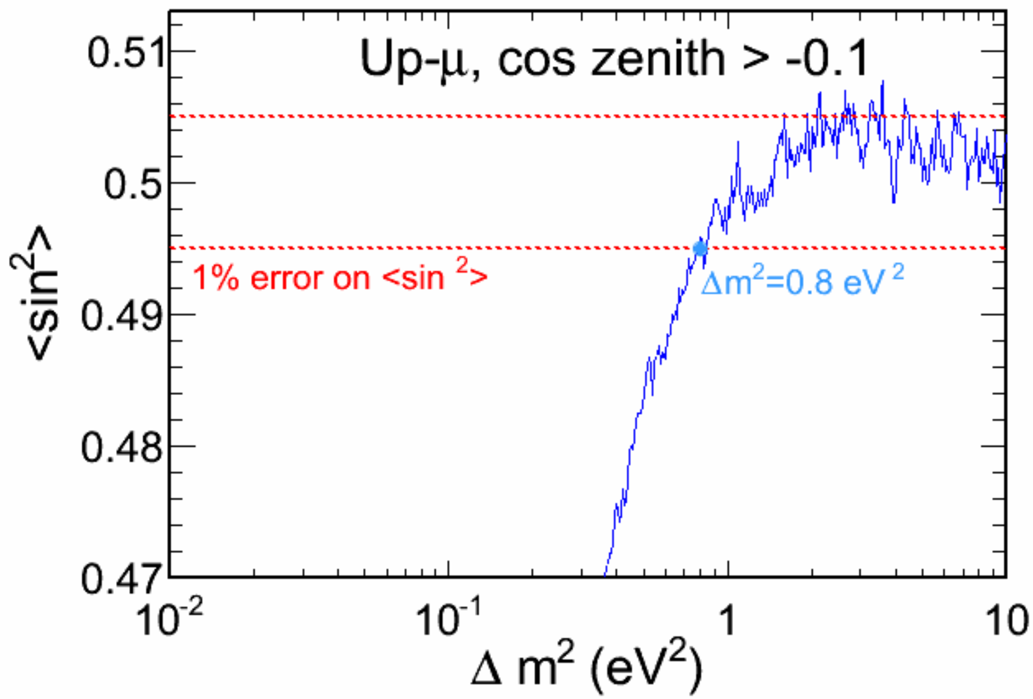
- At right are 2 sensitivities from the 2+1 fit
- The dashed is the normal fit, solid has sterile matter effects arbitrarily turned off
- $|U_{\mu 4}|^2$ limit is unaffected – it is independent of the sterile matter effects



When is Δm^2_{41} no longer "large"?

- When do the oscillations no longer appear fast?
  - This will be the worst at short L's and large E's, so lets focus on Up-μ with cos θ_z > -0.1
  - Loop through all these events and calculate the mean of $\sin^2(\Delta m^2 L/4E)$ for various Δm^2

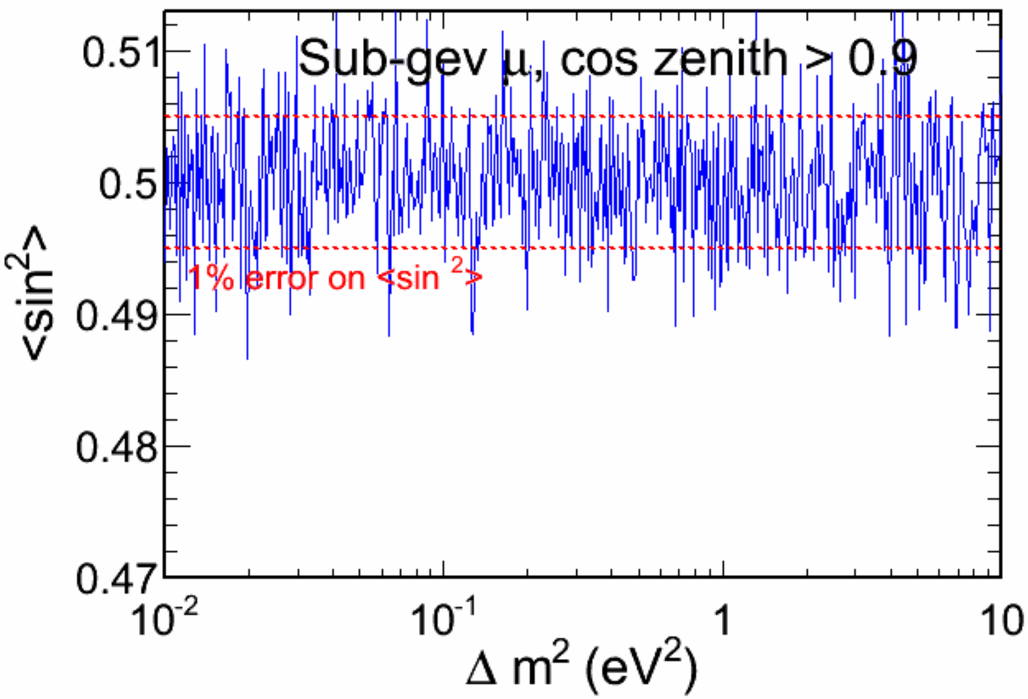
- Doing this, the approximation is valid down to $\sim$0.8 eV^2



When is $\Delta m^2{}_{41}$ no longer "large"?

- However, the limit on $|U_{\mu 4}|^2$ is driven by the low $|U_{\tau 4}|^2$ region.
  - In this region, the dominant samples are Sub-GeV muons
  - Almost no power comes from Up−μ

- For these samples, the "large" assumption is ~always valid so $|U_{\mu 4}|^2$ limit really is a vertical line in Δm^2 to a good approximation



Our Matter Effect Model

- The μ to μ probability is fairly simple:

$$P_{\mu\mu} = (1 - d_\mu)^2 |\tilde{S}_{22}|^2 + d_\mu^2$$

- Get $|S_{22}|^2$ by diagonalizing the sum of the vacuum and matter Hamiltonians:

$$\begin{aligned} H^{(2)} &= H^{(2)}_{sm} + H^{(2)}_{s} : \\ &= \frac{\Delta m^2_{31}}{4E} \begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} \pm \frac{G_F N_n}{\sqrt{2}} \begin{pmatrix} |\tilde{U}_{s2}|^2 & \tilde{U}^*_{s2}\tilde{U}_{s3} \\ \tilde{U}_{s2}\tilde{U}^*_{s3} & |\tilde{U}_{s3}|^2 \end{pmatrix} \end{aligned}$$

Our Matter Effect Model

- This gives us a ~familiar matter-effect probability

$$|\tilde{S}_{22}|^2 = 1 - \sin^2(2\theta_m)\sin^2(f_m L)$$

$$\boxed{\begin{aligned} f_m &= \sqrt{A_{32}^2 + A_s^2 + 2A_{32}A_s\left(\cos(2\theta_{23})\cos(2\theta_s) + \sin(2\theta_{23})\sin(2\theta_s)\right)} \\ E_{1,2}^m &= \pm f_m \\ \sin 2\theta_m &= \frac{A_{32}\sin(2\theta_{23}) + A_s\sin(2\theta_s)}{f_m} \end{aligned}}$$

$$\boxed{\begin{aligned} A_{32} &= \frac{\Delta m_{31}^2}{4E} \\ A_s &= \pm\frac{G_F N_n}{2\sqrt{2}} \\ \sin 2\theta_s &= \frac{2\sqrt{d_\mu d_\tau d_s}}{(1-d_\mu)} \\ \cos 2\theta_s &= \frac{d_\tau - d_\mu d_s}{(1-d_\mu)} \end{aligned}}$$

Our Matter Effect Model

$$P_{\mu\mu} = (1-d_\mu)^2|\tilde{S}_{22}|^2 + d_\mu^2$$

$$P_{\mu\tau} = (1-d_\mu)(1-d_\tau) + (d_\mu(1-d_\mu) \\ - d_s(1+d_\mu))\,|\tilde{S}_{22}|^2 - \sqrt{d_\mu d_\tau d_s}\left(\tilde{S}_{23}\tilde{S}_{22}^* + \tilde{S}_{23}^*\tilde{S}_{22}\right)$$

$$P_{\mu s} = (1-d_\mu)(1-d_s) + (d_\mu d_s - d_\tau)\,|\tilde{S}_{22}|^2 \\ + \sqrt{d_\mu d_\tau d_s}\left(\tilde{S}_{23}\tilde{S}_{22}^* + \tilde{S}_{23}^*\tilde{S}_{22}\right)$$

$$\boxed{\begin{aligned} |\tilde{S}_{22}|^2 &= 1 - \sin^2(2\theta_m)\sin^2(f_m L) \\ \left(\tilde{S}_{23}\tilde{S}_{22}^* + \tilde{S}_{23}^*\tilde{S}_{22}\right) &= -2\sin(2\theta_m)\cos(2\theta_m)\sin^2(f_m L) \end{aligned}}$$

Our Parameters: $|U_{\mu 4}|^2$

- Amount mixing between ν_μ and the sterile mass state ν_4
- Primary effect is extra ν_μ disappearance at all path lengths
- Is directly comparable to SBL measurements of ν_μ disappearance ($\theta_{\mu\mu}$) and indirectly to the MB/LSND appearance signal ($\theta_{\mu e}$)
- With more sterile neutrinos, becomes a more generic parameter d_μ, but out limit is still applicable:

$$d_\mu = \frac{1-\sqrt{1-4A}}{2} \ ,$$

$$A = (1-|U_{\mu 4}|^2-|U_{\mu 5}|^2-|U_{\mu 6}|^2)(|U_{\mu 4}|^2+|U_{\mu 5}|^2+|U_{\mu 6}|^2) \\ +|U_{\mu 4}|^2|U_{\mu 5}|^2+|U_{\mu 4}|^2|U_{\mu 6}|^2+|U_{\mu 5}|^2|U_{\mu 6}|^2 \ .$$

*Conrad, et. al. hep-ex:1207.4765

Our Parameters: $|U_{\tau 4}|^2$

- Amount mixing between ν_τ and the sterile mass state ν_4
- Controls ν_μ->ν_τ vs. ν_μ->ν_s fraction
  – Previous SK sterile measurements have implicitly limited this parameter
- This parameter ~scales the size of sterile-NC matter effects
- Also responsible of NC disappearance over long baselines
- Private to long-baseline and atmospheric measurements
  – But still interesting for understanding atmospheric oscillations